Symbiotic X-ray Binaries

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Outline

1. Symbiotic binaries, the good, bad, and ugly
2. A “typical” S-symbiotic
3. Neutron star symbiotic binaries = SyXB
4. SyXB binary evolution
Symbiotic Stars – SySt
defined by optical spectra that combine high energy emission lines + late type giant features

Allen 1984 ApSS 99 101
Further Divided into S and D types

S-types lack strong IR excess

D (dusty)-types are miras
Modern understanding of symbiotic stars

One of a family of binaries consisting of a late-type star and a hot, compact, usually a white dwarf, companion

SySt class (normal symbiotic binaries) defined by:

• Mass transfer
  - Generates emission line spectrum
  - Roche lobe flow to accretion disk

• Red Giant/AGB + degenerate
  - S-type: Normal M III, orbits of few years
  - D-type: Mira, orbits of decades
Emission lines – UV/Optical problem

Optical Spectrum 4600 – 5050 Å

St 2-22  - Tomov et al. 2017 Acta Astronomica 67 225
IR spectrum 2.0 – 2.5 μm

St 2-22 - Tomov et al. 2017 Acta Astronomica 67 225
IR spectra & data products

• Orbits
  – Time series of spectra spanning years to decades
  – Difficult to get the observations. TACs like short term goals.
  – IR Velocity data: Kitt Peak (coude feed, 2.1 m, 4m), Mt Stromlo 1.9 m, Fairborn 2m, Gemini South
  – 30+ orbits, Fekel, Hinkle, Joyce, et al.

• Abundances
  – IR abundance data – high resolution, high S/N, key spectral features
  – KPNO 4m/Phoenix & Gemini South/Phoenix/IGRINS
  – 20+ stars, Gałan, Mikołajewska, Hinkle, et al.
SySt = observed characteristic not unique evolutionary state

- Multiple evolutionary paths converge to SySt
- Each system needs to be understood separately
Part 2

A “typical” Symbiotic
M III + white dwarf
∴ Progenitor masses both < 8 M\(\odot\)
CI Cyg: M5 II + WD S-type Symbiotic photometry - WD eclipses
Eclipsing symbiotic systems common

- Radius of red star is huge compared to white dwarf

- Binary eclipse criteria: \( a \cos i < R_{rg} + R_{wd} \)
  where \( a = \text{semimajor axis} \)
  \( i = \text{inclination} \)
  \( R = \text{stellar radius} \)
  - \( R_{rg} \) large & semimajor axis typically less than 10 \( R_{rg} \)
    \( \Rightarrow \) large range of \( i \) that eclipses

- Duration of the eclipse a measure of \( R_{rg} \)
## Orbital Elements of CI Cygni

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kenyon et al. 1991</th>
<th>KPNO-Data Solution</th>
<th>Final Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (days)</td>
<td>855.25 (fixed)</td>
<td>855.25 (fixed)</td>
<td>853.8 ± 2.9</td>
</tr>
<tr>
<td>$T$ (HJD)</td>
<td>...</td>
<td>...</td>
<td>2,450,426.4 ± 59.6</td>
</tr>
<tr>
<td>$T_0$ (HJD)</td>
<td>...</td>
<td>2,450,570.4 ± 11.2</td>
<td>...</td>
</tr>
<tr>
<td>$\gamma$ (km s$^{-1}$)</td>
<td>18.4 ± 0.4</td>
<td>15.2 ± 0.3</td>
<td>14.96 ± 0.23</td>
</tr>
<tr>
<td>$K_1$ (km s$^{-1}$)</td>
<td>7.0 ± 0.5</td>
<td>6.7 ± 0.4</td>
<td>6.70 ± 0.30</td>
</tr>
<tr>
<td>$e$</td>
<td>0.0</td>
<td>0.0</td>
<td>0.109 ± 0.048</td>
</tr>
<tr>
<td>$\omega_1$ (deg)</td>
<td>...</td>
<td>...</td>
<td>297.7 ± 24.7</td>
</tr>
<tr>
<td>$a_1 \sin i$ (km)</td>
<td>78.8 ± 9.4 × 10$^6$</td>
<td>78.9 ± 4.7 × 10$^6$</td>
<td>78.2 ± 3.5 × 10$^6$</td>
</tr>
<tr>
<td>$f(m)$</td>
<td>0.027 ± 0.010</td>
<td>0.027 ± 0.005</td>
<td>0.0262 ± 0.0035</td>
</tr>
</tbody>
</table>
M III Radius and Mass

- Distance for Gaia and photometry \( \Rightarrow L = 2261 \, L_{\odot} \)
- Spectral type M5 III \( \Rightarrow T_{\text{eff}} = 3300 \text{K} \)
- \( L = R^2 T^4 \Rightarrow R = 145 \, R_{\odot} \)
- Red giant not Roche lobe filling = “detached”
- Pulsation Period = 50 days \( \Rightarrow \) AGB first overtone
- Pulsation theory for AGB stars:
  \[ \log R = \left( \log P + 0.5 \log M + 1.40 \right) / 1.5 \]
  solve for \( M \) \( \Rightarrow 2 \, M_{\odot} \)
Orbit solution: $f(m) = 0.0262$
Eclipse duration $\rightarrow i = 73°$

$M_{\text{red giant}} = 2 \, M_\odot$

solve for WD mass:

$M_{\text{white dwarf}} = 0.6 \, M_\odot$

From WD initial – final mass relation

MS mass was $\sim 2 \, M_\odot$

*Progenitor MS binary - two similar late A stars*
Part 3

Neutron star symbiotic binaries = SyXB
M III + neutron star

At least one star had
a progenitor M > 8 M☉
Prototype (?) GX1+4=V2116 Oph

- Bright, hard X-ray source
- NS magnetic field $\sim 10^{13}$ G
- X-ray & optical pulsar
  - Very long pulsar P $\sim$2 minutes
  - Variations due to variable mass accretion rate
Orbital period 3.18 yrs

Hinkle et al. 2006 ApJ 641 479
NS mass known (?)

- $M_{NS} = 1.35\pm0.04 \, M_\odot$
  (at least in HMXB)

Thorsett & Chakrabary 1999
M III Radius, Luminosity, & Mass

• Mass function large but no eclipses so
  \[ i \sim 70 \Rightarrow M_{\text{RG}} \sim 1 \, M_\odot \]

• Using standard tricks,
  \[ R_{\text{RG}} = 103 \, R_\odot \]
  \[ L = 1270 \, L_\odot \]

• So red giant is at tip RGB or lower AGB
There must be more than one observable neutron star symbiotic. There are 50 white dwarf – neutron star binaries.

Illustration © G. Booth
8 SyXB found in recent searches

• Search for M III at X-ray coordinates
• Confirm NS with X-ray spectrum
• Optical emission spectrum is weak!
  – V2116 Oph is the exception

V934 Her, $P_{\text{orb}} = 12.0$ yrs

Hinkle et al. in preparation
Mass, etc.

- Gaia D=544 pc, $T_{\text{eff}}=3600$ K, $L=1800$ $L_\odot$, $R=110$ $R_\odot$, $P_{1\text{st overtone}}=44$ days, and the usual tricks:
  - $M_{RG}=1.2 - 1.5$ $M_\odot$
  - $M_{NS}=1.35$ $M_\odot$

- Solve for $i \approx 11^\circ$ viewing nearly pole on
  - Agrees with no pulsar detection.

- $a = 813$ $R_\odot$ so system is detached
Abundances

- For V2116 Oph and V934 Her we have IGRINS and Phoenix spectra
- Measured carbon and oxygen isotopes

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<tr>
<th></th>
<th>V934 Her</th>
<th>V2116 Oph</th>
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<tbody>
<tr>
<td>$^{12}\text{C}/^{13}\text{C}$</td>
<td>10±5</td>
<td>20±5</td>
</tr>
<tr>
<td>$^{16}\text{O}/^{17}\text{O}$</td>
<td>&gt;2500</td>
<td>&gt;2500</td>
</tr>
<tr>
<td>$^{16}\text{O}/^{18}\text{O}$</td>
<td>262±50</td>
<td>1000±200</td>
</tr>
</tbody>
</table>
First dredge up models connect MS mass to \( ^{12}\text{C}/^{13}\text{C} \) and \( ^{16}\text{O}/^{17}\text{O} \)

Smith 1990, Mem Soc. Astron. Italiana 61 787

Figure from Hinkle et al. 2016 ApJ 825 38
Summary of SyXB systems

• M III progenitors were 1.0 – 1.3 M☉ stars
• M III currently:
  – ~1 M☉ (V2116 Oph)
  – 1.2 – 1.5 M☉ (V934 Her)
• M III shows no indication of either significant mass accretion or mass loss
Part 4

SyXB evolution
Constraints

• Massive star passed through supergiant stage
  – $R_{\text{supergiant}} \sim 800 \, R_{\odot}$
  – Overfills **current** Roche lobe size
  – $\therefore$ Orbit evolution

• NS from a supernova
  – CC supernova $\Rightarrow$ kick velocity?
  – Stripped CC supernova, less kick, mechanism?

• Low mass star now RG or early AGB star
  – Mira stage will fill current Roche lobe
Common Envelope Path

- Massive star evolves to overfull Roche lobe
- CE stage reduces mass in system
- Naked helium star \( \rightarrow \) type Ib/c supernova
- Produces NS with low kick velocity

PROBLEM – CE mass loss reduces orbital period from years to days

Willems & Kolb 2002 MNRAS 337 1004
CC Supernova path

- No Roche overflow of evolved massive star
- Core Collapse SN
- Survives if kick is similar to and in opposite direction from orbital velocity
- Result is MS + NS in long period orbit
- Mass transfer during Mira stage spins up NS and expands RL size
- End product is NS + WD long period binary

Willems & Kolb 2002 MNRAS 337 1004
Work in Progress

• Additional SyXB orbits unlikely using open access telescopes
  – Orbits require decade long time series of spectra

• Abundance work in progress – IGRINS
  – M III progenitor mass
  – Progenitor population
  – Traces of SN?
The End